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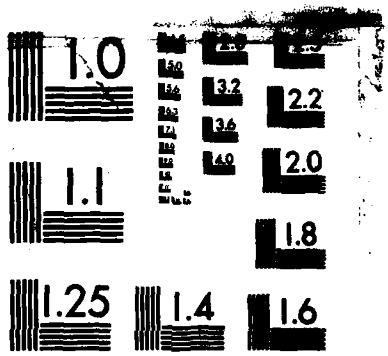
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Calculation of Threshold Conditions for Materials Charging in Maxwellian Plasmas

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25 January 1985

SPACE PHYSICS DIVISION
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Space Plasmas at geosynchronous orbit are usually not characterized by a single Maxwellian distribution function. Plasmas are characterized as single Maxwellians to first order and as a sum of two Maxwellians as a better approximation. A threshold electron temperature condition for charging of materials in the single Maxwellian is derived. Conditions for materials charging in the dual Maxwellian case are derived and illustrated. These are threefold: an initial negative current; a threshold electron temperature and a threshold electron current.

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1. BACKGROUND

DeForest[1] found that the ATS-5 spacecraft, in geosynchronous orbit, charged up to high potentials. Differential potentials of 10 to 12 keV were found to occur on ATS-5 and ATS-6 in eclipse, with occasional charging to several kilovolts in sunlight. DeForest showed that the theory of the Langmuir probe in a plasma provides an explanation of the observed surface potentials. In contrast to laboratory plasma, geosynchronous orbit plasmas have temperatures of many kilovolts. DeForest found that the secondary electron emission due to these kilovolt plasmas must be included in order to account for the observed potentials. Essentially the same result was found by Knott.[2] Since that time, it has been found that the geosynchronous plasma, particularly the electron component, is typically dual Maxwellian, having a hot and a cold population, rather than a single Maxwellian.

(Received for publication 24 January 1985)

1. DeForest, S.F. (1972) Spacecraft charging at synchronous orbit, J. Geophys. Res. 77:651.
2. Knott, K. (1972) Equilibrium potential of a magnetospheric satellite in an eclipse situation, Planet. Space Sci. 20:1137.

Further charging of materials in a dual Maxwellian environment is a more complex phenomenon.[3,4,5] In some cases two stable potentials are possible.

1.1 Charging in a Single-Maxwellian Plasma

In this report we show that materials in a multikilovolt plasma have a charging threshold in a single Maxwellian environment. The threshold electron temperature and charging curves are shown for a variety of spacecraft materials. We show that the controlling parameter for material charging in a one-Maxwellian plasma is the electron temperature. In an environment characterized by a single temperature, a spacecraft whose surface is composed of a variety of materials will charge differentially. Materials with a low threshold will be highly charged while those with a high threshold will be uncharged. In a dynamic situation, in which the electron temperature is varying, because of the existence of a threshold and the steepness of the charging curve above threshold, the potential of a material can jump from zero to kilovolts for a small change in electron temperature.

1.2 Charging in Double-Maxwellian Plasmas

The dual Maxwellian case is frequently encountered at geosynchronous orbit. We derive the necessary and sufficient conditions for charging in a dual Maxwellian environment. In order to charge negatively, the surface must start out with net negative current on it or it will never reach a stable high negative potential. In addition to the electron temperature threshold for charging in a single Maxwellian, there is a threshold in the hot electron current that must be surpassed in order for a surface to charge.

1.3 Charging Conditions

In this report, we consider a material surface immersed in a plasma composed of two species; electrons and ions. The equilibrium potential, V, of the surface will be determined by a current balance equation of the form:

$$J_e(V) + J_i(V) = 0 \quad , \tag{1}$$

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3. Prokopenko, S., and Laframboise, J.G. (1977) Prediction of large negative shade-side spacecraft potentials, Proc. Spacecraft Charging Technology Conference, C.P. Pike and R.R. Lovell, Eds., AFGL-TR-77-0051 and NASA TMX-73537, pp. 369-387.
4. Sanders, N.L., and Inouye, G.T. (1979) Secondary emission effects on spacecraft charging: energy distribution considerations, Spacecraft Charging Technology - 1978, NASA Conf. Publ. 2071.
5. Besse, Arthur L. (1981) Unstable potentials of geosynchronous spacecraft, J. Geophys. Res. 86:2443.

where J_e is the current density due to incident electrons and J_i is that due to ions. These currents will include contribution from secondary interactions and backscatter in the surface material. We will assume that the initial voltage equals zero and that the final equilibrium voltage is negative. In Section 2, we write down the threshold conditions for solutions to Eq. (1) when the plasma can be described by single Maxwellian distributions. In Section 3, we extend the analysis to include double Maxwellian plasmas.

2. THRESHOLD CONDITIONS FOR SINGLE MAXWELLIAN PLASMAS

We consider an object situated in a single Maxwellian plasma. The primary electron current to the surface will be of the form

$$J_e^P(V) = N_e v_e q g_e(V) \tag{2}$$

and the ion current will be

$$J_i^P(V) = N_i V_i q g_i(V) \quad , \tag{3}$$

where we let:

N = plasma number density

$V_k = \left(\frac{kT}{2\pi m_k} \right)^{1/2}$ thermal velocity

T = temperature

m = mass

q = magnitude of electron charge

Subscript k indicates particle species.

The functions $g_e(V)$ and $g_i(V)$ describe the variation in current due to electrostatic repulsion or attraction of the incident particles. The exact forms of g_e and g_i depend on the geometry of the object. For a spherical probe, they would be: $(V < 0)$

$$g_e(V) = \exp\left[eV/kT_e \right] \tag{4}$$

$$g_i(V) = \left[1 - qV/kT_i \right] \tag{5}$$

where T_e, T_i = electron and ion temperatures.

Equation (4) is a Boltzmann factor that reduces the flow of electrons because of the repulsive force. The ions on the other hand are attracted and the current increases by the orbit-limited factor [Eq. (5)].

The secondary and backscatter currents are proportional to the primary incident currents. Thus the net currents can be expressed as

$$J_e(V) = J_e^p(V) \quad \{-1 + \delta^S(T_e) + \delta^B(T_e)\} \tag{6}$$

$$J_i(V) = J_i^p(V) \quad \{ 1 + \delta^S(T_i) \} \tag{7}$$

where we define

$\delta^S(T_e)$ = electron secondaries ratio

$\delta^B(T_e)$ = electron backscatter ratio

$\delta^S(T_i)$ = ion secondaries ratio.

In Eq. (7) we have neglected ion backscatter, which is a small effect. Also, the ratio $\delta^S(T_i)$ will have a slight dependence on V, which we can disregard.

The sign convention in Eqs. (6) and (7) is that negative charge coming to the surface is counted as negative current. All the $\delta(T)$ terms are positive since they correspond to cases where electrons are ejected from the material.

Substituting Eq. (2) into Eq. (6) yields:

$$J_e(V) = N_e \left(\frac{kT_e}{2\pi m_e}\right)^{1/2} q[-1 + \delta^S(T_e) + \delta^B(T_e)]\, g_e(V) \tag{8}$$

and putting Eq. (3) into Eq. (7) gives

$$J_i(V) = N_i \left(\frac{kT_i}{2\pi m_i}\right)^{1/2} q[\, 1 + \delta^S(T_i)]\, g_i(V) \quad . \tag{9}$$

We shall assume, in accordance with Eqs. (4) and (5), that $g_e(V)$ and $g_i(V)$ are positive functions and that $g_e(V)$ approaches zero monotonically as $-V \to \infty$, but $g_i(V)$ is non-decreasing. Our results will thus be valid for any probe geometry for which this is true (such as, spherical, cylindrical, or planar).

It is evident from Eq. (9) that $J_i(V)$ is always positive since this is true for $f_i(V)$ and for the bracket factor. In order for overall current balance to occur in Eq. (1), we must have $J_e(V) < 0$. But from Eq. (8), the only way for this to occur is if the condition

$$\delta(T_e) \equiv -1 + \delta^S(T_e) + \delta^B(T_e) \tag{10}$$

is satisfied. The function $\delta(T_e)$ is plotted in Figure 1 for five different materials. For all temperatures below the point T_e^* where $\delta(T_e)$ crosses zero, no charging is possible. The symbols and material properties assumed are listed in Table 1.

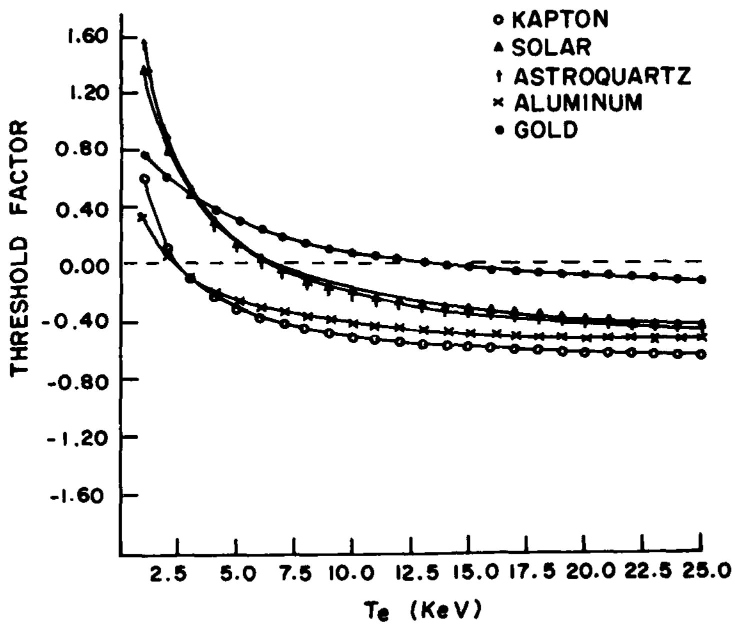

Figure 1. Charging Thresholds for Materials in a One-Maxwellian Plasma. The charging threshold is that electron temperature at which the threshold factor is zero

The terms $\delta^S(T_e)$ and $\delta^B(T_e)$ are shown separately in Figures 2 and 3. The secondary interaction terms $\delta^S(T_e)$ become large at low temperatures while the backscatter term $\delta^B(T_e)$ is relatively flat. When $T_e < T_e^*$ the sum of these coefficients becomes greater than 1 and thus more electrons are ejected from the surface than are arriving from the plasma. The net effect in this case is to discharge the surface.

Equation (10) is a necessary but not a sufficient condition for charging. $J_e(V)$ must not only be negative but it also must be large enough to cancel $J_i(V)$. From our assumption that $g_e(V) \to 0$ as $-V \to \infty$ it follows from Eq. (8) that $|J_e(V)| \to 0$.

Table 1. Material Parameters

Material	Plot Symbol	Electron Secondary $\delta_m E_m$	Ion Secondary 1 keV proton yield $(dE/dX)_m$	Z
Kapton	o	2.1, 0.15	0.455, 140	5
SOLAR	Δ	2.05, 0.41	0.244, 230	10
Astroquartz	+	2.40, 0.40	0.455, 140	10
Aluminum	X	0.97, 0.30	0.244, 230	13
Gold	◊	0.88, 0.80	0.43, 135	79

SOLAR refers to solar cell cover glass material
Astroquartz is a quartz cloth material

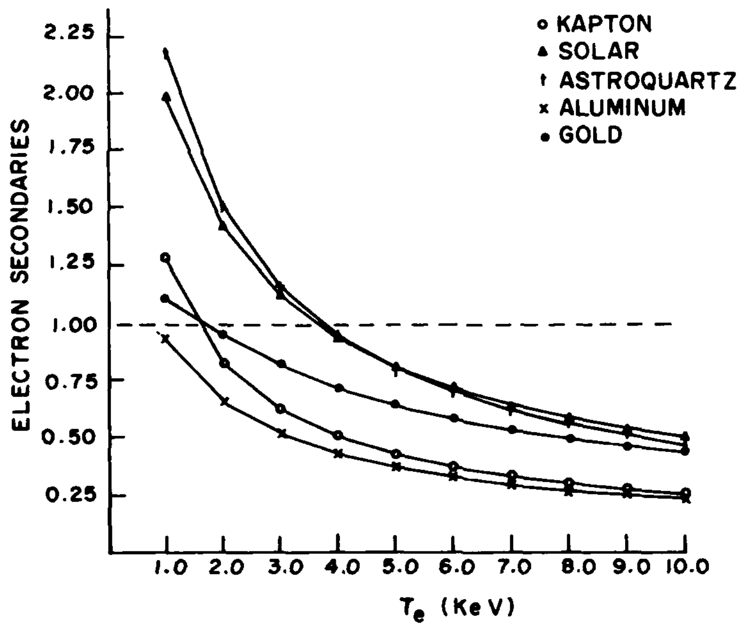

Figure 2. Electron Secondary Emission Yields for Five Materials

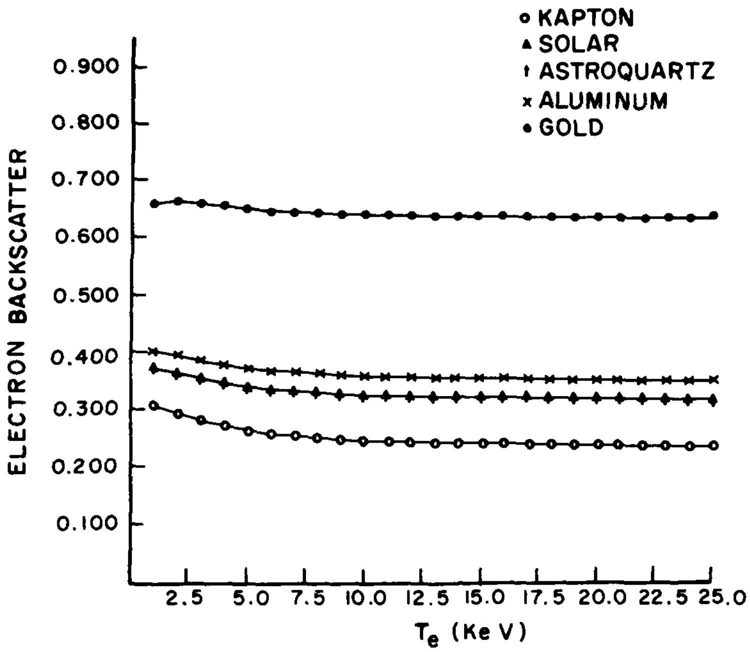

Figure 3. Electron Backscattering Coefficient for Five Materials. Astroquartz and SOLAR are coincident

On the other hand, we have seen that $J_i(V)$ is always positive. Therefore a necessary and sufficient condition for charging is:

$$-J_e(0) > J_i(0) \tag{11}$$

for then, as -V increases, there will be some point at which the function $-J_e(V)$ crosses over $J_i(V)$, that is, the current balance in Eq. (1) will be satisfied. From Eqs. (8) and (9) we can write the conditions of Eq. (11) as

$$-N_e T_e \delta(T_e) > \frac{m_e}{m_i} N_i T_i \delta(T_i) \quad , \tag{12}$$

where $\delta(T_i) = 1 + \delta^S(T_i)$.

The ion secondaries coefficient $\delta^S(T_i)$ is given in Figure 4 for the five materials. The effect of $\delta(T_i)$ is reduced because of the multiplicative factor m_e/m_i [$(1836)^{-1/2}$ for protons]. If the ion term is neglected we recover the previous condition [Eq. (10)].

The dynamics of the charging is illustrated in Figure 5, which shows $-J_e(V)$ and $J_i(V)$ versus V for astroquartz material. Each curve corresponds to a different Maxwellian temperature (T_e, T_i = 5, 10, 15, 20, 25). The plasma densities

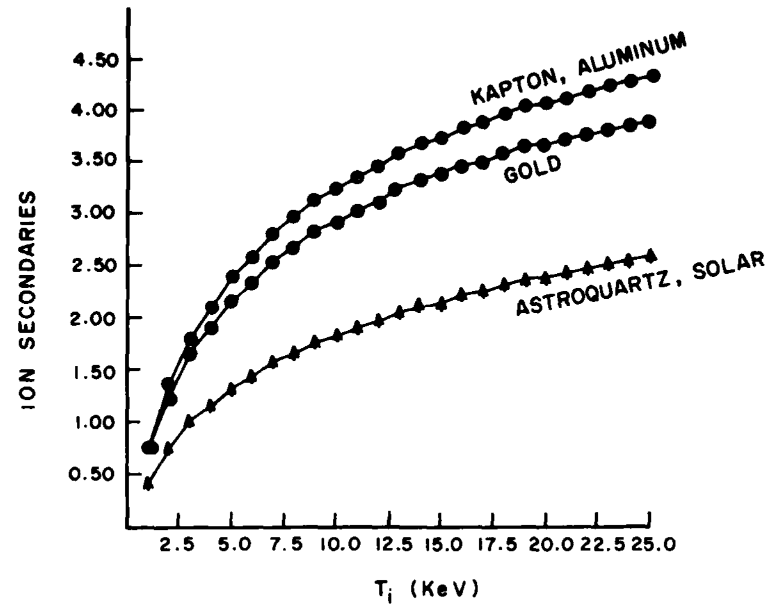

Figure 4. Ion Secondary Emission Yields for Five Materials

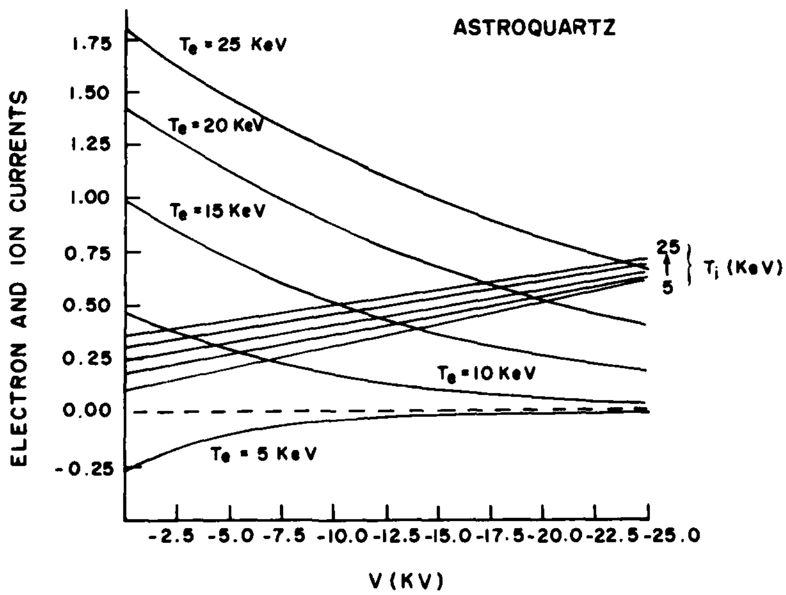

Figure 5. Electron and Ion Currents, Single Maxwellian. The equilibrium surface voltage is defined by the intersection of the electron and ion current curves

are taken as $N_e = N_i = 1$. The intersection of any two curves determines the equilibrium voltage V. The curve for $-J_e(V)$ with $T_e = 5$ lies below the origin and hence can never intercept a $J_i(V)$ line. This is an example of a case where the electron temperature is below the threshold, that is, Eq. (10) is not satisfied and no charging can occur. The remaining $-J_e(V)$ curves start above the $J_i(V)$ lines at $V = 0$ so that the condition of Eq. (11) holds and charging takes place.

Note that there is a greater separation ($\Delta J/\Delta T$) of the electron curves than there is for the ions and therefore the electron temperatures have a stronger influence on the equilibrium voltages. This comes about because the ions have much larger mass and thus the ion currents are smaller by a factor m_e/m_i relative to the electron currents [see Eqs. (8) and (9)]. These computations were carried out with a materials charging code, MATCHG, which is a subset of the NASCAP vehicle charging code.[6]

3. THRESHOLD CONDITIONS FOR DOUBLE MAXWELLIAN PLASMAS

For a multi-Maxwellian plasma, Eqs. (8) and (9) become:

$$J_e(V) = \sum_{j=1}^{n} N_e^j \left(kT_e^j/2\pi m_e\right)^{1/2} \delta(T_e^j)\, g_e^j(V) \tag{13}$$

and

$$J_i(V) = \sum_{j=1}^{Q} N_i^j \left(kT_i^j/2\pi m_i\right)^{1/2} \delta(T_i^j)\, g_i^j(V) \quad , \tag{14}$$

where the superscript j labels the contribution from each Maxwellian component. As before, the ion current $J_i(V)$ is always positive since each term in the summation is greater than zero. Again we must have $J_e(V) < 0$ for charging to occur. The necessary condition for charging is more complicated than for a single Maxwellian. At least one of the T_e^j must be above threshold and the sum of all the contributions to $J_e(V)$ must be negative.

We can see that $J_e(V) \to 0$ as $-V \to \infty$ because each $g_e(V) \to 0$ and the threshold conditions for multi-Maxwellian can be again taken to be Eq. (11). Writing out Eq. (11), using Eqs. (13) and (14), we get

6. Katz, I., Cassidy, J.J., Mandell, M.J., Schnuelle, G.W., Steen, P.G., and Roche, J.C. (1979) The capabilities of the NASA charging analyzer program, Spacecraft Charging Technology - 1978, NASA Conf. Publ. 2071, AFGL-TR-79-0082.

$$- \sum_{j=1}^{P} N_e^j (T_e^j)^{1/2} \, \delta (T_e^j) > (m_e/m_i)^{1/2} \sum_{j=1}^{Q} N_i^j (T_i^j)^{1/2} \, \delta (T_i^j) \quad . \tag{15}$$

For P = Q = 1 we recover the previous result [Eq. (12)]. If the electron distribution can be described by a double Maxwellian (m = 2) then we find

$$N_e (T_e^1)^{1/2} \, \delta (T_e^1) + N_e^2 (T_e^2)^{1/2} \, \delta (T_e^2) < (m_e/m_i)^{1/2} \, F_i \quad , \tag{16}$$

where we have defined

$$F_i = - \sum_{j=1}^{P} N_i^j \, \delta (T_i^{(j)}) \, (T_i^j)^{1/2} \tag{17}$$

The quantity F_i is always negative. Thus to satisfy Eq. (16), at least one of the electron temperatures, say $T_e^{(2)}$ must be above the threshold. From Eq. (16), the borderline in $(N_e^{(2)}, N_e^{(1)})$ space that separates charging and non-charging cases can be written as:

$$N_e^{(2)} = A \, N_e^{(1)} + B \tag{18}$$

with slope and intercept given by:

$$A = - \frac{\left(T_e^{(1)}\right)^{1/2} \delta \left(T_e^{(1)}\right)}{\left(T_e^{(2)}\right)^{1/2} \delta \left(T_e^{(2)}\right)} \tag{19}$$

$$B = \frac{\left(\frac{m_e}{m_i}\right)^{1/2} F_i}{\left(T_e^{(2)}\right)^{1/2} \delta \left(T_e^{(2)}\right)} \quad . \tag{20}$$

4. DISCUSSION

In the dual Maxwellian situation, a typical case is selected to show threshold effects. The material is SOLAR, or solar cell material. A single ion temperature of 10 keV is employed. A low temperature electron Maxwellian at 1 keV is chosen. We show the results of variations of temperature and densities of the hot electron component, since that is the critical component for charging.

Figure 6 shows the boundary lines in $(N_1^{(2)}, N_e^{(1)})$ space, defined by Eq. (18), for aluminum. $T_e^{(1)}$ has been chosen below the threshold temperature and $T_e^{(2)}$ is above it. The regions above the straight line contain those density points for which charging occurs.

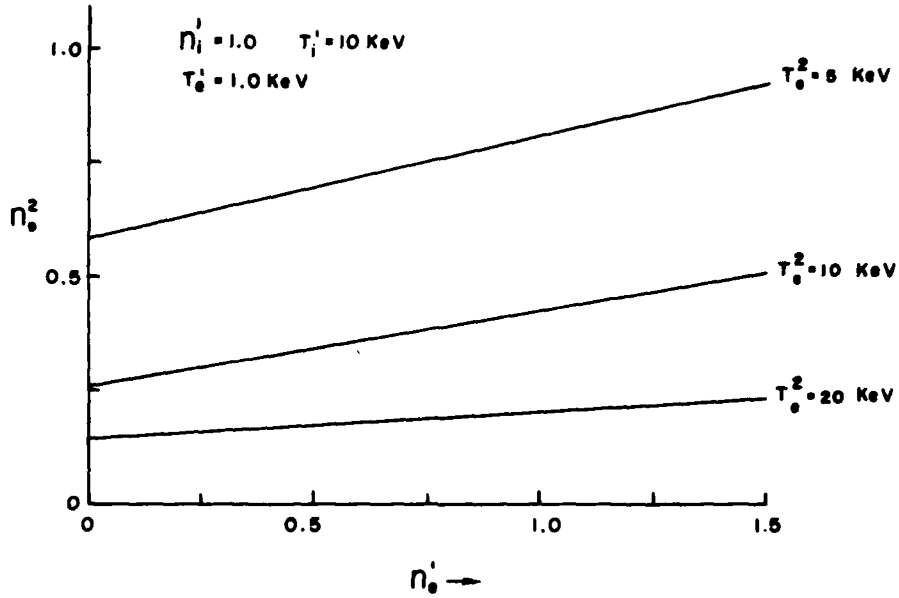

Figure 6. The Boundaries in $(N^{(2)}, N^{(1)})$ Space Separating Charging and Non-Charging Conditions in a Two-Maxwellian Plasma

Figure 7 shows the current voltage curves for a single ion temperature and four cases of two-Maxwellian electrons. The low electron temperature has been chosen to be 1 keV below the charging threshold. The high electron temperatures, $T_e^{(2)}$, are 5, 10, 15 or 20 keV. The charging potentials correspond to the points at which the electron and ion currents intersect, since this is a graphical version of the condition that the net current is zero.

There are four cases. For $T_e = 1, 20$ there is a single root at negative potential. The $T_e = 1, 15$ case has two roots, one stable at V_2 and an unstable root at V_2'. In the $T_e = 1, 10$ case the 2 roots at V_3' and V_3 are close together, and nearly coalesce. The fourth case is for $T_e = 1, 5$ where there are no roots at all.

Starting at zero potential on the material, only one case will be negatively charging. This is the case in which for zero surface potential the electron current exceeds the ion current; otherwise, the surface would charge positively. In a two-Maxwellian plasma, not only must there be a current balance for negative

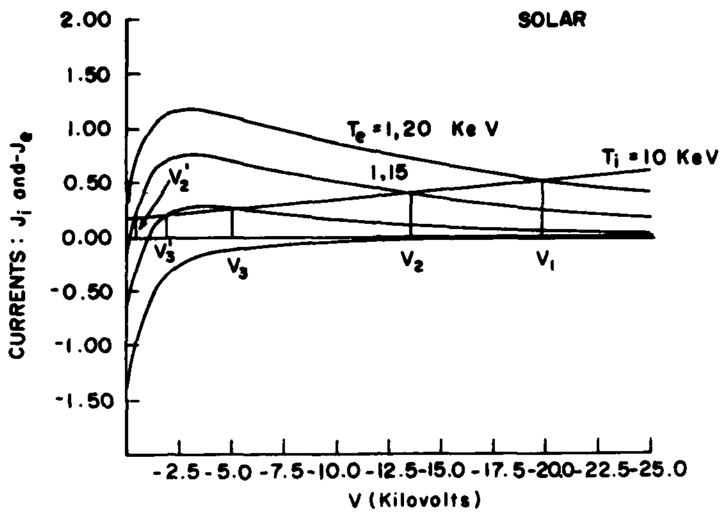

Figure 7. SOLAR Material in a Two-Maxwellian Plasma. The equilibrium surface voltage is again defined by the intersection of the electron and ion current curves. See the text for further details

charging to occur, but also the surface current must start out with net negative current or it will never reach the stable high negative potential.

5. CONCLUSIONS

We have examined the threshold conditions for charging of a surface material immersed in a Maxwellian plasma. The threshold relations depend on the plasma temperatures and densities and on the material properties through the secondary emission coefficients $\delta^S(T_e)$, $\delta^S(T_i)$ and the backscatter ratio $\delta^B(T_e)$. For a single Maxwellian plasma, the necessary condition for charging is that the electron temperature must be greater than the threshold temperature defined by

$$\delta(T_e) = -1 + \delta^S(T_e) + \delta^B(T_e) = 0 \quad .$$

For a multi-Maxwellian plasma at least one of the electron temperatures must be above threshold and the net electron induced current must be negative. To arrive at necessary and sufficient conditions for charging, one has to take into account the ions as well as the electrons. Explicit formulas have been given for single and double Maxwellians [see Eqs. (12) and (16)]. For a double Maxwellian, the threshold condition defines a linearly bounded region in the density space $(N_e^{(1)}, N_e^{(2)})$.

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